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Simulated Acid Rain Effects on Yield Response of Two Corn Cultivars

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Simulated Acid Rain Effects on Yield Response of Two Corn Cultivars¹

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ABSTRACT

Acid rain is a documented phenomenon over much of the eastern and midwestern United States, including major portions of the Corn Belt. However, few studies report the effect of acid rain on yield of corn (*Zea mays* L.). Field experiments were conducted in 1983 and 1984 on a Flanagan silt loam (fine, montmorillonitic, mesic Aquic Argiudoll) soil at Urbana, IL. Two corn cultivars (Pioneer 3377 and B73×Mo17) were protected from ambient rain by two automated movable rain exclusion shelters and were exposed to one of six simulated rain acidities ranging from pH 5.6 to 3.0. Analysis of the effect of rainfall pH on grain yield showed no significant linear or quadratic trend ($\alpha=0.10$) for either cultivar in individual years or with both years combined. Comparisons among treatments for both cultivars showed rain simulants with no added acid (pH 5.6) resulted in grain yields that were not significantly different from the average grain yields of the other five pH treatments. For B73×Mo17, the 2-yr combined yield for the pH 3.0 treatment was significantly lower (5.7%) than the average yield for the other five treatments. This same contrast was not significant for Pioneer 3377. These results imply that under normal environmental conditions and agronomic practices, rainfall at its present levels of acidity has little if any effect on corn yields.

Additional index words: *Zea mays* L., Rain exclusion shelters, Grain yields, pH, Sulfate, Nitrate, Acid precipitation.

ACID precipitation has often been defined as precipitation with pH values less than 5.6 (Likens and Bormann, 1974; Cowling, 1980; Evans, 1982; Jacobson, 1980; Vermeulen, 1980). A pH of approximately 5.6 is the equilibrium pH for the dissolution of ambient atmospheric levels of carbon dioxide (approximately $320 \mu\text{L L}^{-1}$) in water, a reaction that produces carbonic acid (Reuss, 1975). Measured pH values of precipitation in the eastern United States are often lower than pH 5.6 due, primarily, to the oxidation and hydration of sulfur and nitrogen oxides in the atmosphere.

The largest anthropogenic sources of these acidogenic materials result from the combustion of fossil fuels (Cowling and Linthurst, 1981). It has been predicted through the year 2000 that there will be a gradual increase in sulfur dioxide emissions and a substantial increase (by about 25%) in emissions of nitrogen oxides throughout the United States (Interagency Task Force on Acid Precipitation, 1983). These oxides interact with moisture in the atmosphere to

produce elevated atmospheric concentrations of hydrogen ions (H^+), sulfates (SO_4^{2-}), and nitrates (NO_3^-) (Galloway and Whelpdale, 1980).

While there have been several studies on the effects of acid precipitation on crop plants (Evans, 1982; Irving, 1983; Jacobson, 1980; Lee, 1982), the impact of the atmospheric deposition of acidic substances on crop growth and agricultural production is not well understood. There have been only a very limited number of studies involving the effects of simulated acid rain on corn (*Zea mays* L.).

In 1979 at Corvallis, OR, the sweet corn cultivar Golden Midget grown in pots in field chambers was exposed to three applications of simulated acid rain per week in addition to ambient precipitation (Lee et al., 1981; Cohen et al., 1981). In this study the corn was harvested when the plants grew sufficiently tall to interfere with spray from nozzles and, consequently, no grain yields were determined (Lee et al., 1981). Although the foliage exposed to rainfall of pH 3.0 exhibited signs of visible injury, the total above ground weight (stems plus leaves) was greater than that for the control.

In 1980 and 1981 Lee and co-workers (Lee, 1982; Lee, 1982, personal communication) studied the cultivar Pioneer 3992. Acidified simulated rain contained both sulfuric and nitric acids, and simulated rain was applied twice per week. The lowest yield occurred at pH 4.0 in both years (9 and 14% lower than the pH 5.6 control for 1980 and 1981, respectively). No significant differences in yield were noted between the pH 5.6 treatments and the most acidic treatments (pH 3.5 and 3.0). Yield results were similar for three simulated rain events per week in 1980 and two events per week in 1981. In 1982 the same researchers found grain yields for Pioneer 3992 and 'Northrup King PX39' to be unaffected by simulated acid rain treatments that ranged in pH from 3.5 to 5.4, and there was no effect on yield for Pioneer 3992 receiving pH 4.0 treatments differing in ratios of nitric to sulfuric acid, where pH varied from event to event, with the same seasonal average pH for all treatments (Plocher et al., 1985).

The objectives of this research were to establish simulated rain chemistry-yield response functions (treatment-response functions) for two corn cultivars grown under realistic experimental conditions. Treatment-response functions for crop yields are necessary to predict the overall impact of current or anticipated levels of acid precipitation on crops. Six levels of simulated

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rain ranging in pH from 5.6 to 3.0 were employed, and ambient precipitation was excluded.

MATERIALS AND METHODS

Culture

Field studies were conducted during 1983 and 1984 at the University of Illinois Agronomy and Plant Pathology South Farm near Urbana, IL (40°N Lat), on a Flanagan silt loam (fine, montmorillonitic, mesic Aquic Argiudoll) soil. The soil had a cation exchange capacity of 21 cmol (p+) kg⁻¹, and the pH of the surface 0.15 m of soil was approximately 6.3 (Alexander et al., 1974). The land used for the experiment had been planted in wheat (*Triticum aestivum* L.) in 1982. Wheat stubble was chisel plowed to a depth of 0.25 m in the fall of 1982. In the spring of 1983 the plot area was fertilized, tilled with a disc-harrow, a field cultivator, and rototilled. The herbicides Sutan + (S-ethyl diisobutylthiocarbamate plus) (Stauffer Chemical Co., Westport, CT), Bladex (2-[4-chloro-6-(ethylamino)-S-triazin-2-yl]amino-2-methylpropionitrile) (Shell Chemical Co., Modesto, CA), and atrazine (2-chloro-4-ethylamino-6-isopropylamino-S-triazine) (Shell Chemical Co., Modesto, CA) were applied prior to rototilling at rates of 4.66 L ha⁻¹, 5.45 kg a.i. ha⁻¹, and 5.45 kg a.i. ha⁻¹, respectively. Fertilizer additions were based on soil tests and included N, P, and K at the recommended rates of 224, 56, and 112 kg ha⁻¹, respectively (University of Illinois College of Agriculture, 1982). The land used in the 1984 experiment had been in wheat in 1982 and soybean [*Glycine max* (L.) Merr.] in 1983. Seed bed preparation and soil amendments for corn were the same for both years of the experiment. The average annual pH of ambient rain at this site is approximately 4.3 [National Atmospheric Deposition Program (NADP), 1985].

Genotypes and Plant Populations

The corn hybrids selected, B73×Mo17 (Illinois Foundation Seeds, Inc., Champaign, IL) and Pioneer 3377 (Pioneer

Hi-Bred International, Princeton, IL) were chosen because of sensitivity to drought stress and high commercial yields in Illinois, respectively. Seeds were hand planted on 28 Apr. 1983 and 1 June 1984. In 1983 the corn received ambient rainfall until the nozzle system was completed on 6 June. Corn was overplanted and thinned to achieve the desired population of 64 600 plants ha⁻¹.

Experimental Design

The experimental design consisted of a split plot with the main plot arranged in a randomized complete block design. The variable for main plots was one of six simulated rain acidity levels, and cultivar was the split plot variable. Each split plot contained three 3.05-m rows of corn spaced 0.51 m apart. The harvest area of the split plot consisted of two rows 2.44 m long by a total width of 1.02 m, as shown in Fig. 1.

Statistical analyses were carried out using the Statistical Analysis System (SAS Institute, 1982). When appropriate, Error a and Error b of the split plot design were pooled to gain precision for testing treatment effects. The significance level selected for pooling was $\alpha = 0.25$ (Carmer et al., 1969).

Yield results in 1983, 1984, and with both years combined were analyzed using four specific contrasts: (i) pH linear, (ii) pH quadratic, (iii) pH 3.0 versus the average of the other five treatments, and (iv) pH 5.6 versus the average of the other five treatments. If the pH linear or pH quadratic contrasts were significant, the other two contrasts were considered irrelevant. Since the pH treatment levels were unequally spaced, orthogonal coefficients for the contrasts were calculated using the methods of Carmer and Seif (1963).

Rain Exclusion Shelters

Corn plots were protected from ambient rainfall by two movable rain exclusion shelters (Oehmsen Plastic Greenhouses, Bohemia, Long Island, NY), each 10.4 m wide, 41.5 m long, and 6.1 m high at the peak. They were constructed

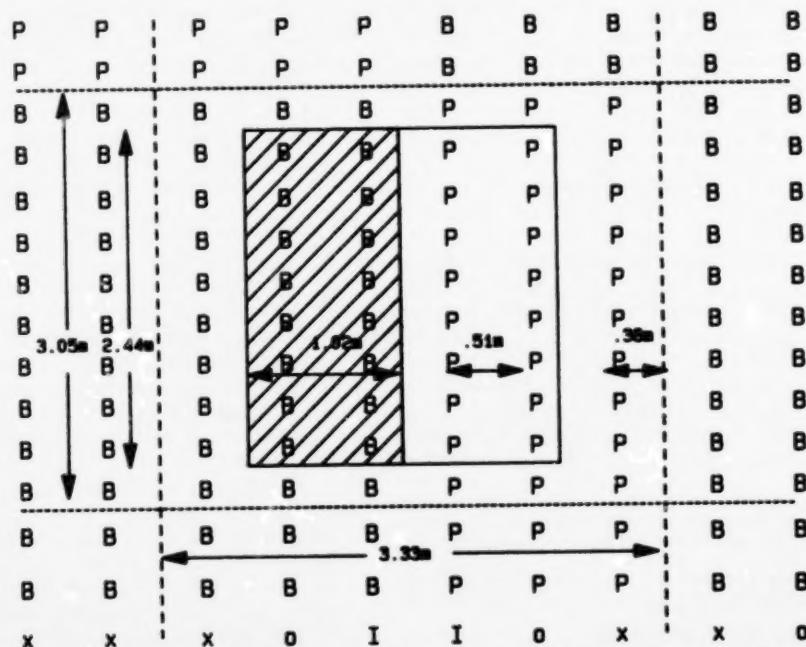


Fig. 1. The 3.05- by 3.33-m main plot, which was split by two cultivars (P = Pioneer 3377 and B = B73×Mo17). The shaded area represents the harvest area of one split plot. Each row in the harvest area of the split plot contained approximately eight plants. The 'x, I, and o' refer to the border, inner, and outer rows, respectively.

Table 1. Concentration and total deposition of background ions in simulated rain.

Ion	Concentration	Total deposition	
		1983	1984
	mg L ⁻¹	kg ha ⁻¹	
Ca ²⁺	0.165	0.520	0.537
Mg ²⁺	0.035	0.110	0.114
K ⁺	0.031	0.098	0.101
Na ⁺	0.169	0.533	0.551
NH ₄ ⁺	0.258	0.813	0.840
Cl ⁻	0.107	0.337	0.349
PO ₄ ³⁻	0.007	0.022	0.023

of galvanized pipe framing and covered with standard 0.15-mm greenhouse plastic (Ethyl Corp., Vis-queen Division, La Grange, GA). An automatic rain sensor triggered shelter movement on a rail system so that the crops were covered within 60 s of the first drops of rain. Crops were covered only during ambient rainfall events and when simulated rain was applied through a nozzle system mounted in the structures.

Simulated Rain Chemistry and Application

Simulated rain contained specific amounts of anions and cations based on the weighted average ion concentrations in ambient rain for NADP sites in New York, Pennsylvania, and Ohio for the period 1 June through 30 Sept. 1979 (Irving et al., 1982). These background ions, listed in Table 1, were added to ultra pure (approximately 17 megohms) water obtained by processing city water through separate-bed cation and anion exchange resins and then through mixed-bed resins. The pH of the simulated rain was adjusted to one of six acidity levels with sulfuric and nitric acids at a constant sulfate/nitrate ratio of 3:1:1 on an equivalent basis. The H⁺, SO₄²⁻, and NO₃⁻ concentrations of the six pH treatments are listed in Table 2. Each simulated rain treatment was batch equilibrated in one of six 3200 L tanks (United States Plastic Corp., Lima, OH) to assure proper rain chemistry before application. The pH of the simulated rain was monitored by six inflow pH meters (Model 942 pH Monitor, Beckman Industrial Corp., Lombard, IL), and by taking grab samples and analyzing them on a separate pH meter (Model 825MP, Fisher Scientific Co., Pittsburgh, PA). The amount of simulated rain applied and the application rate were monitored during each rain event by electronic flow meter-accumulators (MK575R Accum-U-Flo, Signet Scientific, El Monte, CA). In addition, rainfall collectors were used to measure nozzle output and to insure accurate delivery. One 'Fulljet' nozzle (No. 1/8G8W, Spraying Systems Co., Wheaton, IL) with a wide angle, full cone spray pattern treated each main

Table 3. Experimental and environmental parameters.

	1983 and 1984	
Simulated rain pH values	5.6, 4.6, 4.2, 3.8, 3.4, and 3.0	
Frequency of application	2 week ⁻¹	
Time of application	1600 to 1900 h	
Duration of application	32 min rain time (48 min total)	
Simulated rain intensity	19.5 mm h ⁻¹	
Droplet size	1.2 mm	
Total deposition per rain event	10.5 mm	
	1983	1984
Planting	28 Apr.	1 June
First simulated rain	6 June	15 June
Last simulated rain	16 Sept.	28 Sept.
Harvest began	12 Oct.	9 Nov.
Number of simulated rain events	30	31
Total amount of simulated rain per plot	316 mm	326 mm
Avg daily maximum temperature (July-Aug.)	31.7°C	29.2°C
Avg daily minimum temperature (July-Aug.)	20.2°C	16.9°C
Avg daily pan evaporation (July-Aug.)	5.7 mm	5.0 mm

Table 2. Concentration and total deposition of H⁺, SO₄²⁻, and NO₃⁻ ions in simulated rain.

pH	H ⁺	NO ₃ ⁻	SO ₄ ²⁻	Total deposition			
				1983	1984		
				Concentration	kg ha ⁻¹		
				mg L ⁻¹			
5.6	0.003	0.46	1.11	0.01	1.4	3.5	0.01
4.6	0.03	0.84	2.02	0.08	2.6	6.4	0.08
4.2	0.06	1.41	3.42	0.20	4.4	10.8	0.21
3.8	0.16	2.84	6.74	0.50	9.0	21.2	0.52
3.4	0.40	6.44	15.24	1.25	20.3	48.0	1.30
3.0	1.00	15.50	36.59	3.15	48.9	115.4	3.26

plot. Nozzles were adjusted several times throughout the growing season so as to remain approximately 1.5 m above the crop canopy. Details of rain applications are given in Table 3. Total time of each rain event was 48 min, consisting of a 16-min application, a 16-min period to allow for infiltration and to avoid surface runoff, and another 16-min application. The total amount of simulated rain added to the plots was equivalent to the average amount of rain received during the growing season in Urbana, IL, for the last 30 yr (National Oceanic and Atmospheric Administration, 1982). No supplemental irrigation was provided.

RESULTS AND DISCUSSION

Grain Yields

Grain yields, adjusted to 155 g kg⁻¹ moisture, for the six simulated rain treatments are shown in Table 4. In both 1983 and 1984, as well as for the 2 yr combined, there were significant cultivar effects ($\alpha=0.0001$, 0.0016, and 0.0001 for 1983, 1984, and both years combined, respectively) and cultivar $\times$ year interactions ($\alpha=0.001$). However, there were neither significant ($\alpha=0.10$) pH effects nor significant pH $\times$ cultivar interactions. While the main effects were not significant, some of the contrasts evaluated showed significant pH $\times$ cultivar interactions. Therefore the cultivars are discussed separately.

B73 $\times$ Mo17

The average grain yield for each pH treatment for the 2-yr combined data is graphed in Fig. 2. In 1983,

Table 4. Grain yields† for the six simulated rain treatments and the level of significance of the tested contrasts.

pH treatment	B73 $\times$ Mo17			Pioneer 3377		
	1983	1984	Avg	1983	1984	Avg
	kg ha ⁻¹					
5.6	11 000	14 010	12 500	12 640	13 940	13 290
4.6	11 510	13 520	12 520	13 090	14 790	13 940
4.2	10 680	13 860	12 270	12 570	13 420	13 000
3.8	11 510	13 460	12 480	12 920	14 080	13 500
3.4	11 550	13 320	12 440	12 630	14 070	13 350
3.0	10 260	13 270	11 770	13 020	14 790	13 910
Avg	11 080	13 570	12 330	12 810	14 180	13 500
	Levels of significance					
Contrasts	1983	1984	Combined	1983	1984	Combined
pH linear	0.51	0.18	0.15	0.72	0.44	0.41
pH quadratic	0.10	0.97	0.28	0.97	0.46	0.58
5.6 vs. rest	0.80	0.27	0.49	0.61	0.54	0.42
3.0 vs. rest	0.01	0.45	0.03	0.53	0.12	0.11

† The CV for yield was 10.44% in 1983, 10.77% in 1984 and 10.66% for years combined.

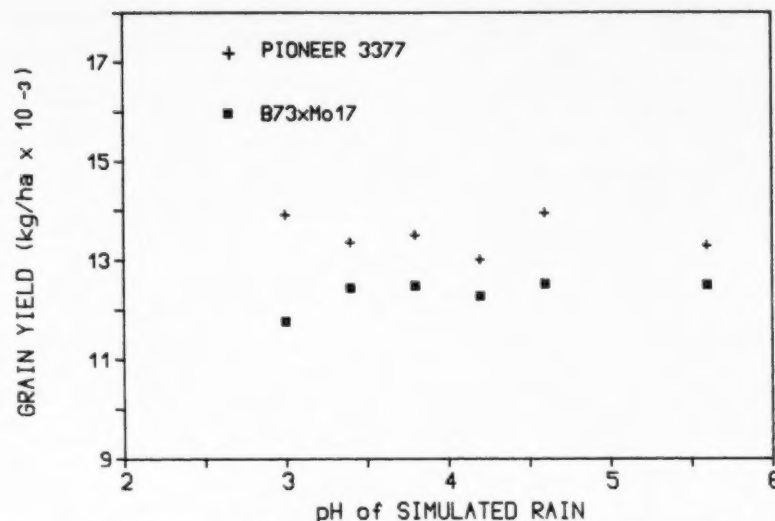


Fig. 2. The average grain yield (in kg ha⁻¹) for B73×Mo17 and Pioneer 3377 for 1983 and 1984 combined. Each data point represents the average of 24 replications (12 replications per year, of each pH level). For B73×Mo17 the yield at pH 3.0 was significantly less than the average yield for the other five pH treatments.

1984, and with the 2-yr combined data there were no significant pH linear or pH quadratic trends. It should be noted, however, that for this cultivar the grain yield associated with the pH 3.0 treatment was lower than that of the other treatments for both years of the experiment. Yield at pH 3.0 was 560 kg ha⁻¹ (4.8%) less than the yield for the average of the other five pH treatments for the combined 1983 and 1984 (significant at $\alpha=0.03$), and 820 kg ha⁻¹ (8.0%) less for the 1983 data (significant at $\alpha=0.01$). Yield at pH 3.0 was not significantly different from the average of the other five pH treatments in 1984 ($\alpha=0.45$). The difference in yield between the pH 3.0 treatment and the average yield of the other five pH treatments was much greater in 1983 than in 1984. Since the 1983 growing season was warmer than average, it is possible that under heat stress the most acidic pH treatment may have had more of an effect on grain yield for B73×Mo17. It is also possible that pH 3.0 is a threshold value and that increased acidity would result in even greater yield reductions for this cultivar. This hypothesis, however, has not been tested.

In no instance was the comparison of the pH 5.6 treatment versus the average of the other five pH treatments significant. The pH 3.0 treatment yields were the lowest observed for both years, but the range in yields for among treatments varied by less than 10% for any given year.

Pioneer 3377

The average grain yield for each pH treatment for the 2 yr combined is shown in Fig. 2. In 1983, 1984, and with the 2-yr combined data there were no significant pH linear or pH quadratic trends (Table 4). In 1983, 1984, and with the 2-yr combined data the comparison of the pH 3.0 treatment versus the average of the other five pH treatments and the comparison of the pH 5.6 treatment versus the average of the other five pH treatments were not significant ($\alpha=0.10$). For

Pioneer 3377, the pH 3.0 biweekly treatment resulted in one of the higher measured grain yields.

It should be emphasized that the vast majority of the studies on the effects of acid deposition on crops are actually studies of the effects of simulated acid rain on crops. The effects on crops of precipitation other than rain, such as dew, mist, and fog, have not been studied in much detail. In addition, dry deposition may play a role in crop response to acid precipitation, but very few studies have included an analysis of the effects of dry deposition. There are at present no standard methods for measuring the amount of dry deposition, and effects of dry deposition on crops are unknown (Kerr, 1981).

Visible Damage

No visible foliage damage due to the simulated rain treatments was observed at any stage of growth for either of the cultivars despite biweekly applications of simulated rain as low as pH 3.0.

Border Effects

Yield data were analyzed to determine if there was a border effect on grain yield. Each main plot contained three rows of one cultivar adjacent to three rows of the other cultivar (Fig. 1). Since only the four center rows were harvested, one harvest row for each cultivar (outer) had the same cultivar growing on each side, whereas the other harvest row (inner) had the same cultivar growing on one side and the second cultivar growing on the other side.

The difference in yield between the inner row and the outer row for each split plot (cultivar) was determined. A paired *t*-test of this difference indicated no significant yield difference between the inner row and the outer row in 1983, but in 1984 and with both years of data combined there were significantly higher yields for the outer row than for the inner row (Table 5). For both years of data combined, the difference in yield

between the inner and outer rows was 600 kg ha⁻¹, or 4.8%. The yield differences observed in these subsamples of each split plot do not effect the overall experimental results since there were an equal number of inner and outer rows for all treatments and replications. However, these results document the importance of border effects in field experiments.

It is speculated that there was an increase in light penetration to the outer rows as compared to the inner rows. Increased light penetration to the outer rows could have been due to: (i) a greater distance between blocks (0.76 m) than between rows within blocks (0.508 m), and (ii) the border rows, particularly those near the rails of the shelter, tended to be smaller because of less moisture, allowing increased light penetration to the outer rows.

CONCLUSIONS

In both 1983 and 1984 the yield for B73×Mo17 averaged over all pH treatments was approximately 10% less than the yield for Pioneer 3377. However, the results indicate no significant linear or quadratic effects of simulated rainfall pH on grain yields of either cultivar. No yield differences were noted for either cultivar when the control treatment (pH 5.6) yields were compared to the average yields of the other five pH treatments. There were cultivar differences when comparing the yields at the most acidic treatment (pH 3.0) to the average yields of the other five treatments. The yield for Pioneer 3377 was not affected, but the yield for B73×Mo17 was less than the average of the other pH treatments. Results from this study suggest that simulated acid rain, at levels less acidic than ambient conditions, applied twice weekly throughout the growing season did not affect grain yields of two corn cultivars. At levels more acidic than ambient conditions, the yields for one cultivar were not affected, whereas yield for the other cultivar at the most acidic level was significantly decreased.

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Table 5. Inner and outer row yields and the paired t-test of their differences.†

	1983	1984	Both years
Inner row mean	11 840 kg ha ⁻¹	13 380 kg ha ⁻¹	12 610 kg ha ⁻¹
Outer row mean	12 050 kg ha ⁻¹	14 370 kg ha ⁻¹	13 210 kg ha ⁻¹
t	-0.91	-3.66	-3.36
P > t†	0.36	0.04	0.09

† Inner rows have one cultivar on one side and the other cultivar on the other side. Outer rows have the same cultivar on both sides.

‡ The probability that the difference between the yield for the inner and the outer row for each cultivar in the main plot is equal to zero.